Energy Research and Development Division
FINAL PROJECT REPORT

INCREASING RENEWABLE ENERGY BY ALMOND SHELL GASIFICATION

Catalytic Converter and Emission Reduction Report

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PREFACE

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Increasing Renewable Energy by Almong Shell Gasification: Catalytic Converter and Emission Reduction Report is one of three final reports for the Increasing Renewable Energy by Almond Shell Gasification project (contract number 500-10-048, work authorization number POEF01-S11 and POEF05-D12 conducted by Univerisy of California. The information from this project contributes to Energy Research and Development Division's Buildings End-Use Energy Efficiency Program and the Renewable Energy Technologies Program.

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ABSTRACT

This research project used clean fuel gas from the gasification of almond biomass to: optimize gasification, develop advanced gas cleaning, and reduce combustion exhaust emissions. The results of this project, Increasing Renewable Energy by Almond Shell Gasification, are presented in three reports: *Almond Biomass Characterization* (publication number: CEC-500-2016-056), *Tar Reforming and Tar Removal* (publication number: CEC-500-2016-057), and *Catalytic Converter and Emission Reduction* (publication number: CEC-500-2016-058).

In the third report for this project, Catalytic Converter and Emission Reduction, researchers test simulated producer gas based on the gasification characteristics of almond biomass. Tests were done in a Cooperative Fuel Research engine at the Colorado State University Engine Laboratory to determine performance and emission reduction methods. Lean combustion limit, engine knock compression ratio (Methane Number), and nitrous oxide (NOx) and carbon oxide (CO) combustion emission characteristics were determined.

Keywords: Almond Biomass, Tar Reforming, Partial Oxidation, Catalysts, Gasification, Producer Gas, Methane Number, NOx, CO, Lean Combustion.

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EXECUTIVE SUMMARY

Introduction

With approximately 6,000 growers, California produces 80 percent of the world's almonds and 100 percent of the U.S. commercial supply. Almonds also rank as the largest U.S. horticultural export. Almond processing produces large quantities of by-products that can be used for energy and other applications. Almond shells are one of the most important of these potential feedstocks produced during post-harvest processing after almonds are collected from the field. There are two basic types of almond post-harvest processing facilities: hullers that provide hulled (the outer coat), in-shell almonds as a final product, and hullers/shellers that yield hulled, shelled and almond meats as a final product. Each year California's almond harvest typically produces more than a million tons of biomass waste including 454,000 tons of shells.

During the last several years, interest has increased in using these by-products at higher efficiency or in more local cogeneration facilities to replace natural gas and support state level Renewable Portfolio Standards to reduce greenhouse gas emissions from fossil based fuel combustion. Understanding the impacts of chemical and combustion characteristics that almond shell feedstock have on engines is imperative to effectively using this by-product in gasification facilities to generate electricity.

Project Purpose and Process

Burning agricultural biomass such as almond shells using advanced dual-fluidized-bed designs generates a producer gas with high hydrogen content, low nitrogen diluent content, and a relatively high heating value. Using this high quality producer gas as a fuel for internal combustion engines, while meeting regulatory emission standards, requires an understanding of producer gas engine performance and emissions including methane number, engine knock, efficiency, and carbon monoxide (CO) and nitrogen oxide (NOx) emissions. Identifying these feedstock qualities allows engines to operate at maximum efficiency with reduced emissions.

The project team determined the performance of producer gas and emission characteristics for two typical producer gas blends. The two producer gas blends (40 percent volume and 33 percent volume of hydrogen) and one natural gas blend were compared with each other during operation in a Cooperative Fuel Research (CFR) test engine. For each blend, the Methane Number was determined which is a measure of resistance to engine knock. This is similar to the octane number for gasoline, except for the Methane Number, the reference blend is a methane/hydrogen mixture. Ignition timing was varied and evaluated for optimal efficiency and emissions. The equivalence ratio was varied and emissions measured until the lean limit was reached.

Regulatory limits for stationary engines in California are currently set at 0.07 lb/MegaWatthour (0.03 g/kiloWatthour) NOx, 0.10 lb/MWh (0.04 g/kWh) CO, and 0.02 lb/MWh (0.01 g/kWh) VOC. Engines with a high efficiency have an advantage in achieving these limits.

For producer gas, lean-burn engines are especially attractive, because they can operate at higher compression ratios, achieve more complete burnout of the fuel, and have a working fluid composition closer to that of air. The technology used this project was a lean-burn engine with an after-treatment to reduce NOx and CO emissions. Since the Selective Catalytic Reduction (SCR) technology with an oxidation catalyst reduces pollutants by more than 90 percent, the goal is to reach emissions low enough so combined with the exhaust cleanup, emission limits can be reached. High hydrogen content of producer gas provides the opportunity to operate engines at a lower lean limit, i.e. lower equivalence ratio, than for natural gas. Compared with natural gas, the high concentration of hydrogen in the producer gas promotes the onset of engine knock, requiring a lower compression ratio. The Methane Number is a measure of resistance to engine knock and is evaluated experimentally by increasing the compression ratio until engine knock occurs. This is similar to the Octane Number for liquid fuels. If a blend achieves a knock resistance equal to a mixture of 70 percent methane and 30 percent hydrogen, its Methane Number would be 70. The research team vared the compression ratio of the engine conducted on a CFR research engine which has this unique capability.

Project Results

Researchers found the Methane Number was lower for the producer gas blends than for the natural gas blend. The producer gas blend with 40 percent hydrogen had a slightly lower Methane Number (MN 65) than the blend with 33 percent hydrogen (MN 68). The team concluded engines operating on producer gas required a lower compression ratio which reduces efficiency. Combustion statistics indicated the producer gas blends burn faster and more stable than the natural gas blends increasing efficiency. Producer gas blends can reach leaner operating conditions than natural gas blends, significantly lowering their NOx emissions. While at the same equivalence-ratio, producer gas has higher power-specific NOx emissions, at the lower lean limit, these emissions are less than natural gas. CO emissions are higher for producer-gas blends because of the large amount of CO in the fuel.

Project Benefits

Producer gas blends from biomass gasification can offer similar NOx emissions and efficiencies as those for natural gas, if they are operated at lower equivalence ratios. This provides an avenue for reducing greenhouse gas emissions, while simultaneously generating lower NOx and unburnt hydrocarbon emissions. Producer gas creates higher CO emissions and must be addressed with a well designed oxidation catalyst. It is recommended to verify the emission characteristics of producer gas blends that contain other contaminants such as ammonia. To reduce emissions below regulatory limits, SCR catalysts must be tested with producer gas blends to confirm their performance. These tests should include oxidation catalysts as well, because of the higher CO emissions of producer gas.

CHAPTER 1: Catalytic Converter and Emission Reduction

This project determined the Methane Number (MN) of two producer gas blends. Once the Methane Number was determined, the critical compression ratio was evaluated. The second objective measured the emissions near the lean limit at a compression ratio below the critical compression ratio.

The characterization of three fuel blends was conducted, two simulated producer gas variations and one simulated natural gas blend. Three characterization experiments were conducted: (1) Methane Number to define engine knock limits, (2) Ignition timing at lean condition ($\varphi = 0.7$) to determine performance and emissions (NOx and CO), and (3) equivalence-ratio sweeps with engine boost pressure increased to simulate turbo charged engine operation to determine engine performance and emission levels.1.1.

1.1 Producer Gas Performance and Emission Reduction in a CFR Engine

1.1.1 Apparatus and Procedure

The test cell used for this research is capable of conducting engine operations with virtually any producer-gas fuel blend desired. Engine operational parameters that are controllable include compression ratio (r), mean effective pressure (MEP), intake boost pressure, intake temperature, exhaust back-pressure, air-fuel ratio, and ignition timing. The type of engine used in this project is a Cooperative Fuel Research (CFR) F-2 model manufactured by Waukesha Engine, Dresser Industries (Figure 1). It is a stationary, constant-speed (e.g. 900 rpm), un-throttled, single-cylinder, 4-stroke engine with a cylinder bore of 3.250 inches (8.255 cm) and piston stroke of 4.500 inches (11.43 cm) [2]. The displacement volume of the engine is 37.33 in^3 (611.7 cm3). The compression ratio is variable from 4:1 to 18:1.

1.1.1.1 Engine Test-Cell Capabilities

The following is a summary about the capabilities of the CFR engine test cell.

The improved ignition system permits maximum brake torque (MBT) evaluation. The engine, originally configured with a capacitive discharge type ignition system, is currently configured with an electronic ignition system (Altronic model CD200) adapted to a single-cylinder engine.

The blending system is capable of producing blends of desired constituent composition. A fuel blending system was developed and integrated with the engine for evaluation of alternative gaseous fuels. A schematic of the system is shown in Figure 2.

The engine has the ability to increase brake mean effective pressure (BMEP) to levels closer to typical lean-burn natural-gas engines by boosting intake. The laboratory compressed-air system was utilized for the engine air supply, permitting engine operation at boosted intake pressure.

The setup has the ability to increase the exhaust pressure in order to simulate the demand from a turbocharger. An exhaust-backpressure-control system was developed to apply backpressure to the engine.

One major aspect of the test engine is the capability of precise knock quantification and Methane-Number measurement. The CFR-engine-detonation sensor was replaced with a piezoelectric sensor (Kistler Model 6061b) whose raw signals are routed to a charge amplifier and further processed. A Fast-Fourier-Transform (FFT) algorithm was developed within the LabVIEW combustion logger to indicate a signal magnitude at the characteristic knock frequency. This program feature is used to establish a knock index value to provide an objective measure of knock intensity for comparison of conditions using a test fuel blend and a reference fuel blend. The reference blend is composed of methane and hydrogen. The Methane Number is defined as the percent methane in the reference blend that produces the same knock intensity as the test blend at the same compression ratio.

Additional details on the test cell and methane-number measurement can be found elsewhere [3, 4, 5].

Figure 1: Waukesha Variable-Compression-Ratio CFR Engine, Modified for Gaseous Fuel Operation

Emissions from the engine were measured using a Horiba PG-250 Portable Multi-Gas Analyzer. For this, a slip stream was sampled from the exhaust and dried in an ice-trap. The gas analyzer then drew a slip stream from the dried gas flow. The emissions of NOx, CO, CO_2, and O_2 were recorded. For reporting emissions in ppmd@15%O2 or as brake-specific emissions (g/kWhr), the raw readings were adjusted accordingly.

1.1.1.2 Test Matrix

Tests were conducted on three different blends. The composition of the blends is shown in Table 1. Blend 1 (40% H_2) represents a producer gas with large amounts of hydrogen, as could be obtained by gasification with high amounts of steam and long residence times. Blend 2 (33% H_2) represents a producer gas that has slightly less hydrogen and more carbon monoxide (CO). This blend could be more energy efficient for power production, where a large H_2/CO ratio might not be required. Blend 3 (90% CH_4) represents a simulated natural-gas blend and is used for comparison.

In Table 2, the test plan is summarized by grouping the testing into three separate tests. Methane-Number measurements performed during the first experiment are conducted for five (I to V) different test conditions given in Table 3. For each engine-operating condition, the compression ratio is increased until knock occurs. The purpose of this test is to examine the sensitivity of the Methane-Number measurement to different engine operating conditions. Case I represents the nominal Methane-Number measurement conditions, consistent with the original development by Leiker et al. [3]. The other cases represent deviations from these conditions commonly encountered in industrial natural-gas engines. During the test, the critical compression ratio (rcrit) is also obtained for each Methane Number measured. For Test 2, an ignition-timing sweep was performed for each blend. The purpose of this test was to evaluate the optimum ignition timing for each fuel blend and to document the emission variations with ignition timing. Test 3 consisted of equivalence-ratio sweeps for each blend to evaluate the lean limit for each fuel and to explore emissions variation with equivalence ratio.

Figure 2: Schematic Depiction of the Test Cell Fuel Blending System

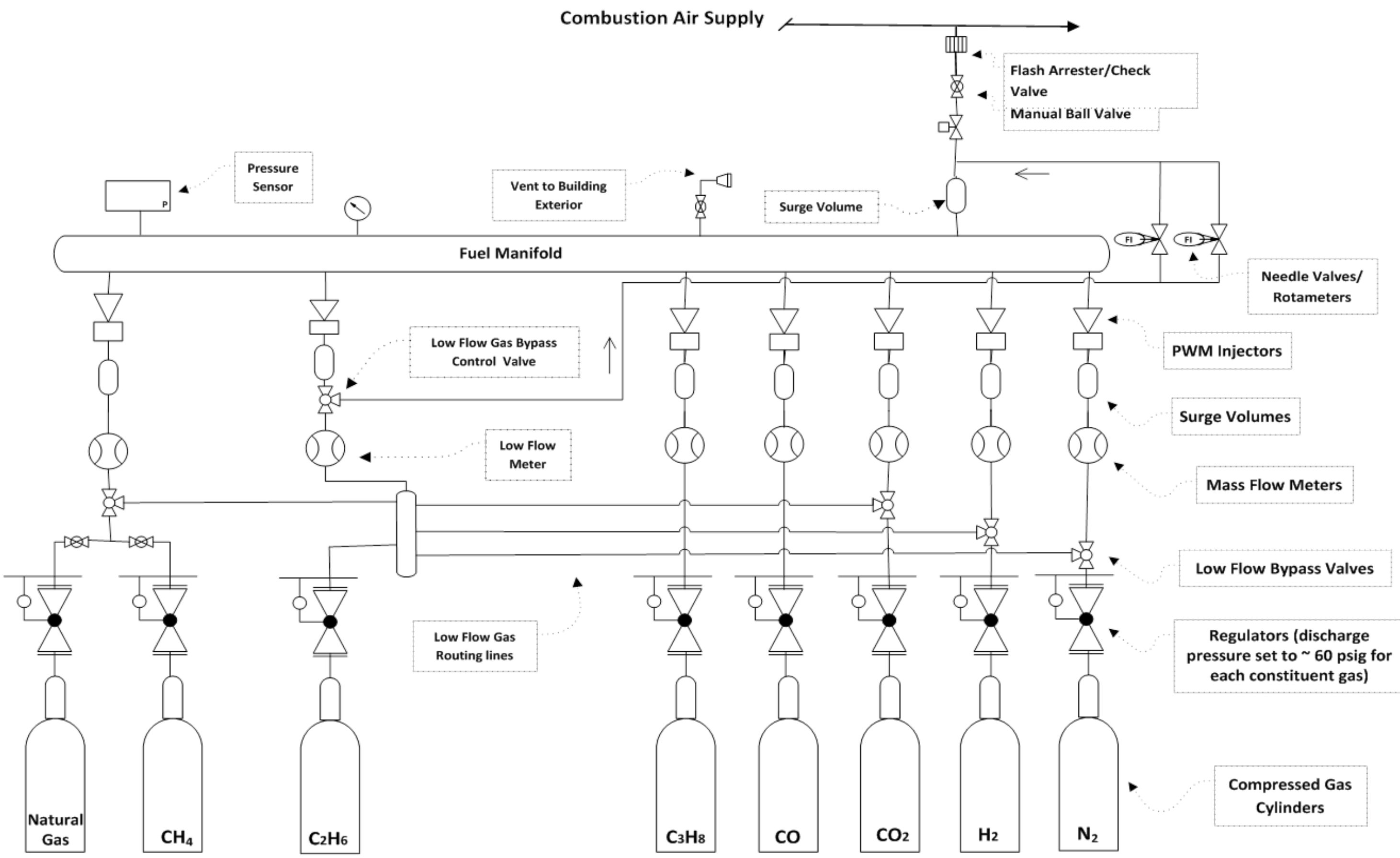


Table 1: Target Gas Blend Compositions

	Blend 1	Blend 2	Blend 3
Methane (CH4) [vol%]	10	10	90
Ethylene (C2H4) [vol%]	3	3	0
Ethane (C2H6) [vol%]	0	0	10
Carbon Monoxide (CO) [vol%]	24	31	0
Carbon Dioxide (CO2) [vol%]	23	23	0
Hydrogen (H2) [vol%]	40	33	0
Lower Heating Value [MJ/Nm3]	12.69	12.81	38.56
Lower Heating Value [MJ/kg]	14.16	13.11	49.66
A/Fs	4.20	3.85	17.04
A/F @ ϕ=0.7	5.99	5.50	24.34

Table 2: Test Plan Summary

Test Number	Test Description Summary	Fuel	Condition	Objective
1	Methane Number Measurement	Blend 1 Blend 2 Blend 3	5 Cases	Methane Number, Sensitivity to Operating Parameters, rcrit
2	Ignition Timing Sweeps	Blend 1 Blend 2 Blend 3	ϕ=0.7 r = 9.6 NMEP = 10 bar	Evaluate optimum timing, emissions profile
3	Φ sweeps	Blend 1 Blend 2 Blend 3	NMEP = 10 bar r = 9.6 LPP = 15°	Evaluate lean limit, emissions profile

Table 3: Operating Cases for Methane Number Measurements

Case #	Ignition Timing	NMEP/Intake Boost	ϕ
I	17°bTDC	NA – 101.3 kPa	1.0
II	23°bTDC	NA – 101.3 kPa	1.0
III	17°bTDC	10 bar NMEP	1.0
IV	23°bTDC	10 bar NMEP	0.7
V	23°bTDC	10 bar NMEP	1.0

1.2 Results and Discussion

1.2.1 Determination of Methane Number

Figure 3 presents Methane-Number measurements for each blend. In every case, Blend 3 (90% CH_4) has the largest Methane Number, which indicates that it is most resistant to knock. This is expected, since Blend 3 is simulated natural gas, whereas Blend 1 (40% H_2) and Blend 2 (33% H_2) are producer-gas blends. The producer-gas blends have high levels of CO and H_2. These species are more reactive and tend to knock more readily. The main knock-promoting species in the Methane-Number reference blend is hydrogen, therefore blends with higher hydrogen are expected to knock more readily. The Blend-2 (33% H_2) Methane Number is larger than Blend 1 (40% H_2) in every case. This can be explained by Blend 1 having more hydrogen than Blend 2. There is substantial variation in Methane Number among cases I-V, but the relative relationship between the fuel blends remains largely the same. This indicates that the Methane Number is an accurate metric for assessing the knock tendency of fuels, even if the engine operating conditions for the end-application are different than the operating conditions for the standard

Methane Number measurement (Case I). It is noted that when comparing the results obtained closest to standard test conditions to those closest to typical lean-burn engine-operating conditions (comparing Case I to Case IV) the variation in measured methane number is less than 10%.

The critical compression ratio was recorded for each Methane-Number measurement and compiled in Table 4. Generally, the critical compression ratio follows the Methane Number. That is, fuels that are more knock resistant have both larger Methane Numbers and larger critical compression ratios. Fuels that are more knock resistant can operate safely in engines with larger compression ratios, which achieve higher brake-thermal efficiencies. The measured critical compression ratio is a less reliable measure, because uncontrolled engine-operating conditions, such as ambient air humidity, can change from day-to-day. The Methane Number is more consistent because the reference blend is tested right after the test blend in every case. The general trend of increasing critical compression ratio with increasing Methane Number holds in all but one case (case IV). The average critical compression ratio for all five cases is given in the last column of Table 4. The average critical compression ratio of Blend 3 (90% CH_4) is 1.1 units higher than for Blend 1 (40% H_2), with Blend 2 (33% H_2) falling in between. This highlights a disadvantage of producer gas compared to natural gas. Producer-gas fuels tend to knock more readily and cannot operate at as high of compression ratios as natural gas.

Figure 4 shows engine power employing the three different fuels under the varying operating conditions. Cases I and II are naturally aspirated and Cases III, IV, and V are controlled to 10 bar net mean effective pressure (NMEP). The power generated in Cases I and II varies with the fuel composition, whereas the power generated in Cases III, IV, and V is essentially held constant by controlling NMEP at 10 bar. Significantly more power is generated for Blend 3 (90% CH_4) for Cases I and II, since the lower heating value (LHV) is higher (see Table 1) for simulated natural gas compared to the simulated producer gas.

Figure 3: Measured Methane Number for Three Test Blends Under Differing Operating Conditions

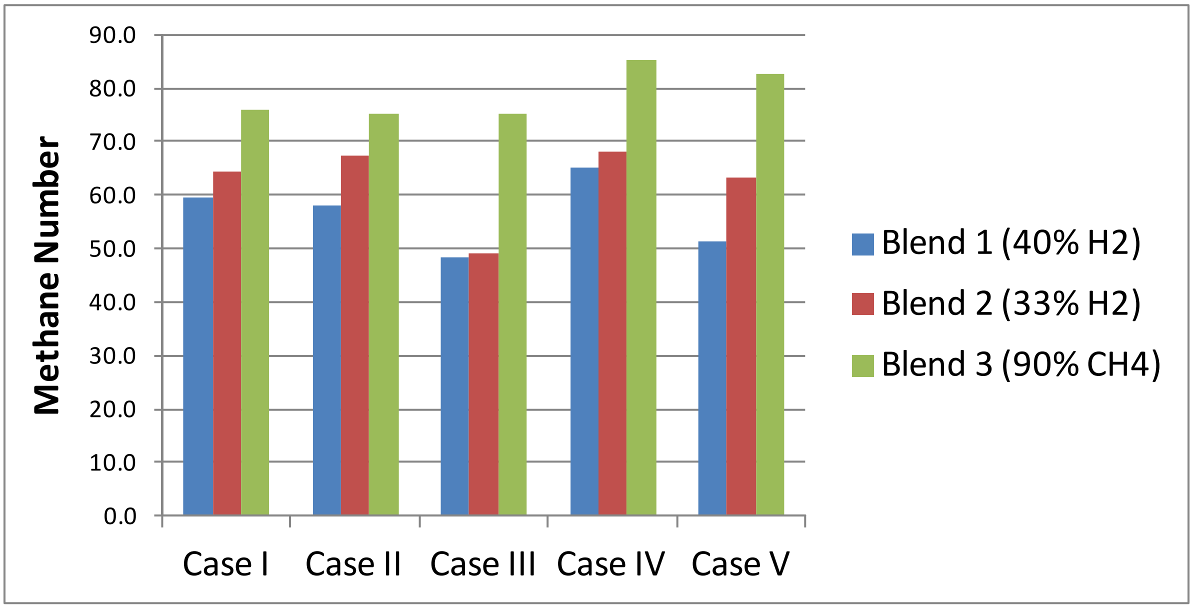


Table 4: Critical Compression Ratios (rcrit) for Test Blends

Blend	rcrit Case I	rcrit Case II	rcrit Case III	rcrit Case IV	rcrit Case V	rcrit Average
1 (40% H_2)	9.7	9.2	8.7	8.8	8.2	8.9
2 (33% H_2)	9.9	9.8	9.2	8.4	9.5	9.4
3 (90% CH_4)	11.1	10.0	9.2	10.5	9.2	10.0

Figure 4: Power Output at Stipulated Operating Conditions for the Three Tested Gas Blends

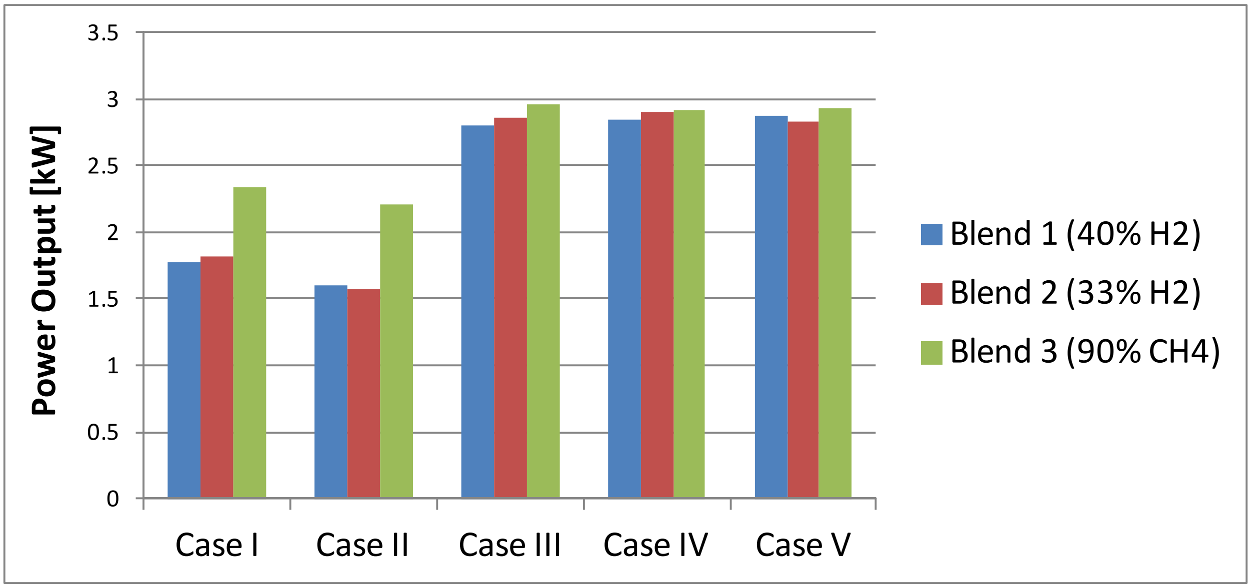


Figure 5 plots brake-thermal efficiency for cases III, IV, and V. Cases I and II are not shown, since those cases are at different power levels. Significantly higher efficiencies are measured for Blend 3 (90% CH_4) compared to producer gas. The data is collected at the critical compression ratio (higher for simulated natural gas), which is one reason why the thermal efficiency is higher for Blend 3 (90% CH_4). Figure 6 shows the amount of intake boost required to attain an NMEP of 10 bar (Cases I and II are naturally aspirated; Cases III, IV, and V are boosted). For the 10-bar cases (III, IV, and V), Blends 1 and 2 require much higher levels of boost because their LHVs are much lower than of Blend 3. This highlights an operational difference for producer gas engines. To obtain the same power density (NMEP) as natural gas, a producer gas engine will require significantly more boost (~18%). This may require a different turbocharger design.

Table 5 shows combustion-pressure statistics for two of the five cases. Included in the table are pumping mean effective pressure (PMEP), location of peak pressure (LPP), coefficient of variation (COV) of NMEP, mass fraction burn (MFB) duration 10-90%, and MFB 0-10%. The PMEP data shows that the pumping loss is larger when the engine is boosted (Case IV). LPP, MFB 10-90%, and MFB 0-10% are all indicators of the rate of combustion. Case I is complicated by the fact that the power levels are different for each blend. The Case IV blend tests are at a constant power level, so the data provide a comparison of combustion rates that better isolates the effect of the fuel type. For Case IV, the data show that Blend 1 (40% H_2) and Blend 2 (33% H_2) burn at a faster rate than Blend 3 (90% CH_4). LPP occurs earlier and MFB 10-90% and 0-10% durations are shorter. This represents an advantage of producer gas over natural gas. A faster-burning fuel allows the combustion event on average to take place near top-dead center, when the compression is highest. In general, the ignition timing would be adjusted to be later so that LPP is around 15 °aTDC. This is done in subsequent tests, but the Methane Number experiments were conducted at fixed ignition timing (Table 3). It is interesting that the producer gas blend that burns fastest is Blend 2, which has less H_2 but more CO than Blend 1. COV NMEP indicates combustion stability. A lower value indicates a more stable combustion event. That data show that blends with faster combustion are more stable (lower COV NMEP).

Figure 5: Thermal Efficiency at Differing Operating Conditions for Three Test Blends

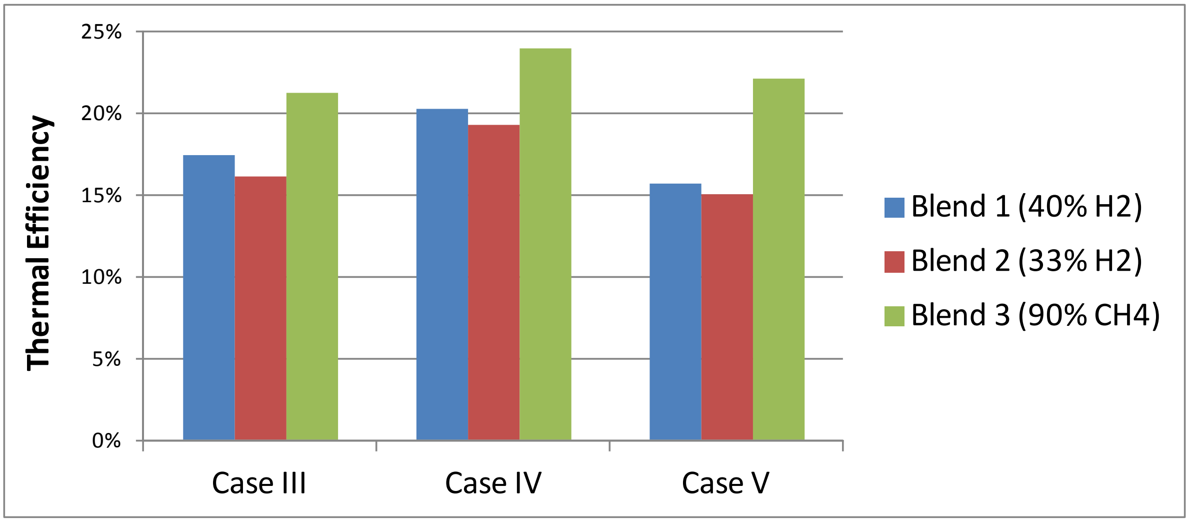


Figure 6: Intake Boost Recorded for Each Test Blend to Achieve Stipulated Operating Conditions

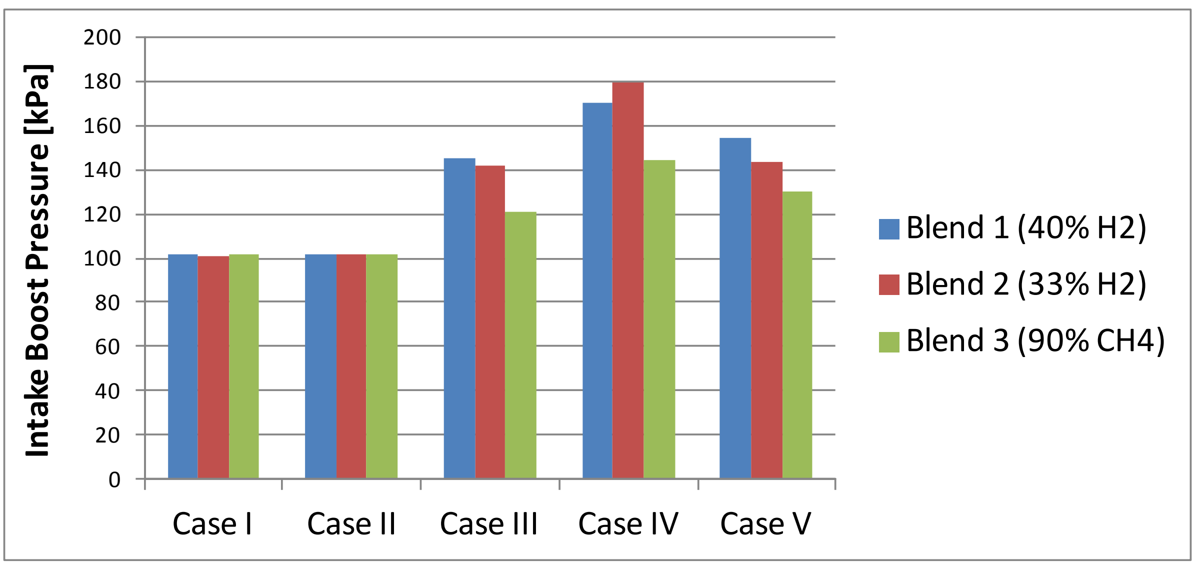


Table 5: Engine Performance Data for Case I and Case IV

Case		PMEP [kPa]	LPP [°aTDC]	COV NMEP [%]	MFB 10-90 [°CA]	MFB 0-10 [°CA]
I	Blend 1 (40% H_2)	-19.7	10.0	2.0	32.9	10.0
	Blend 2 (33% H_2)	-22.1	10.6	1.7	29.3	10.7
	Blend 3 (90% CH_4)	-25.1	13.4	1.6	28.9	12.9
IV	Blend 1 (40% H_2)	-61.9	9.4	1.6	20.4	13.4
	Blend 2 (33% H_2)	-53.2	6.0	1.4	19.0	9.8
	Blend 3 (90% CH_4)	-59.7	14.0	2.3	24.0	17.5

1.2.2 Ignition Timing Sweeps

For ignition timing experiments, the compression ratio was fixed at 9.6 for all tests, and the NMEP and equivalence ratio were held constant at 10 bar and 0.7, respectively. Figure 7 shows the thermal efficiency of the engine with each fuel blend as a function of ignition timing. Also shown in the plot is LPP. As ignition timing increases (more advanced), the LPP decreases, occurring closer to TDC. For Blends 1 and 2, the timing could not be advanced as much as Blend 3 due to a knock limit. Efficiency is relatively insensitive to ignition timing. All blends show an optimum ignition timing value, but the curves are relatively flat. For simulated natural gas (Blend 3), the optimum occurs between 23 and 24°bTDC. The data indicate that the optimum timing for the producer gas (Blends 1 and 2), based on thermal efficiency, occurs between 19 and 20°bTDC. The optimum timing for all fuels results indicates a LPP in the range 13-16°aTDC. The combustion phasing of producer gas is shifted (advanced) by approximately 7°. Blends 1 and 2 show slightly higher efficiency values compared to Case IV above. This is because the compression ratio for the ignition timing sweeps is significantly higher than the critical compression ratios for methane number testing.

Figure 7: Thermal Efficiency as a Function of Ignition Timing

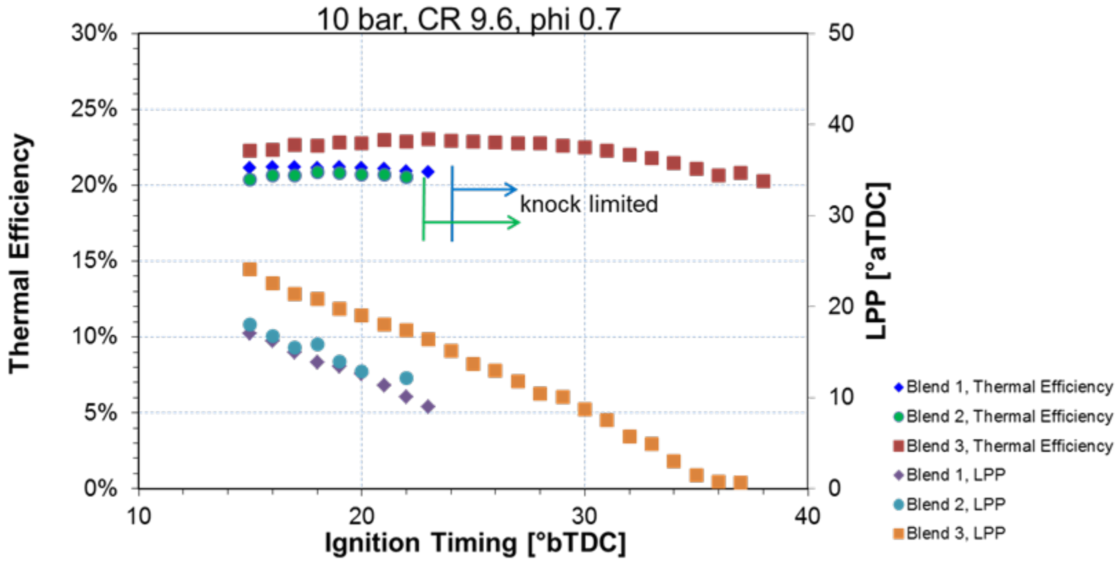


Figure 8 shows NOx production as a function of ignition timing, given in parts per million (dry) at 15% oxygen (O2). Expression of emissions based on 15% O2 normalizes the amount of dilution air in the exhaust. The NOx values increase as timing is advanced, which results in earlier peak pressures and higher combustion temperatures. The figure shows Blends 1 and 2 producing much higher levels of NOx for the same ignition timing. However, the ignition timing can be adjusted to achieve the same NOx level of Blend 3. For example, to achieve a NOx level of 700 ppmd at 15% O2, the ignition timing values for Blends 1, 2, and 3 would need to be 16, 15, and 19°bTDC, respectively. Figure 9 shows CO levels for each blend as a function of ignition timing. It can be seen that ignition timing variation does not result in significant variation in CO production. CO emissions for producer gas (Blends 1 and 2) are significantly higher (~3X) than simulated natural gas (Blend 3). This is due to the fact that there is a significant amount of CO in the fuel. These blends contain 24 and 31% CO, respectively. Unlike NOx, the ignition timing cannot be adjusted to reduce CO emissions to the level observed for the natural gas blend.

Figure 8: NOx Emissions Recorded at Each Increment of Ignition Timing

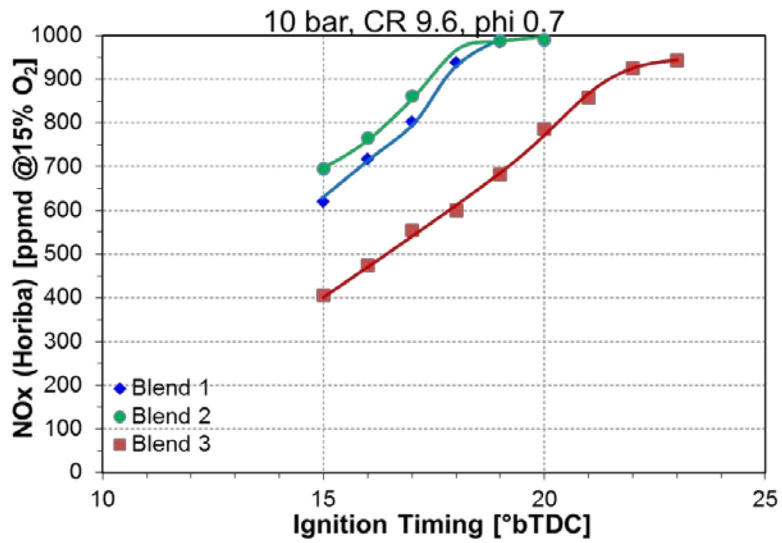
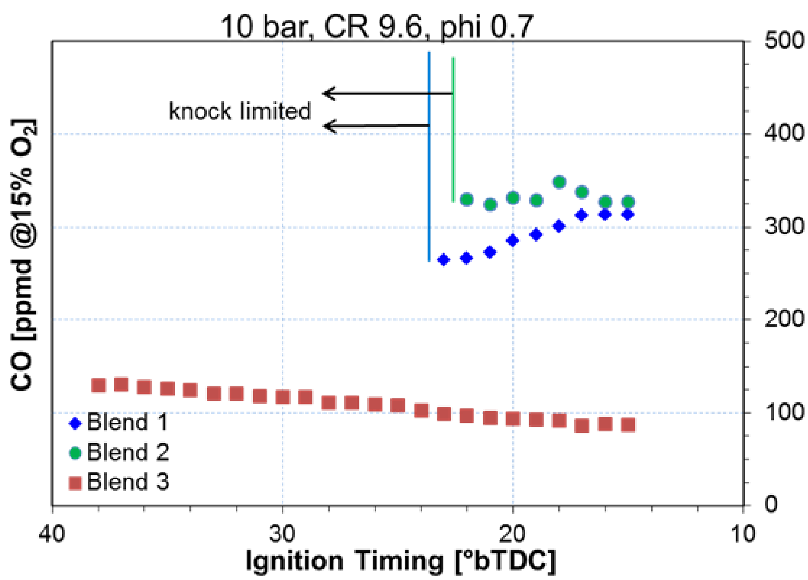


Figure 9: CO Emissions as a Function of Ignition Timing

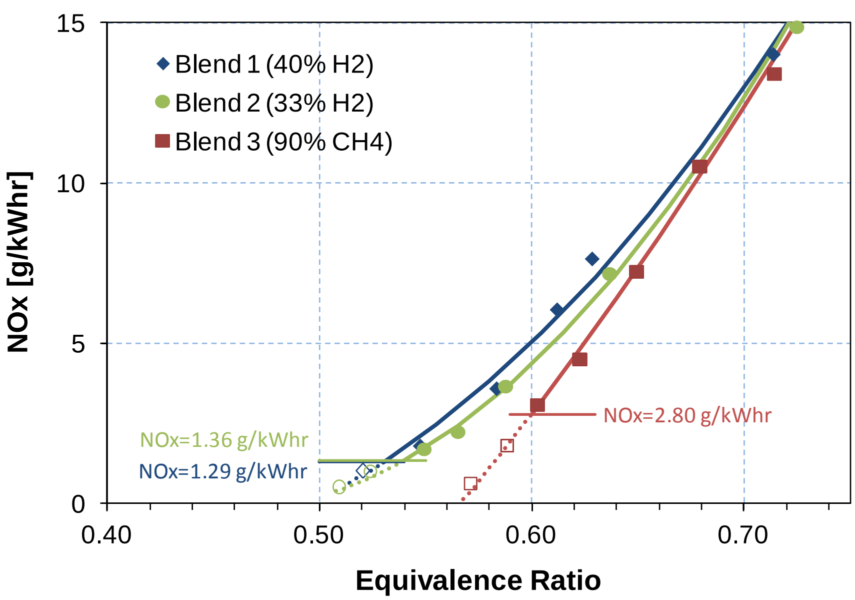


1.2.3 Equivalence Ratio (Phi) Sweeps

Data was collected starting at slightly lean conditions and reducing the equivalence ratio until the lean limit was exceeded. Here, the lean limit was defined as the point at which the coefficient of variation (COV) for NMEP exceeded a value of 5.0%. The coefficient of variation is defined as the ratio of the standard deviation to mean value and is recorded in real time in the data collection process. Equivalence-ratio sweeps were conducted with all three blends at a compression ratio of 9.6 at constant NMEP (10 bar). Emissions were sampled and recorded continuously as well as combustion data. The actual equivalence ratio was determined through analysis of the emissions data utilizing the method published by Urban et al. [6]. It is noted that the Urban and Sharpe method does not accommodate equivalence ratios greater than 1.0. The emissions are converted to brake-specific emissions by taking in account the exhaust flow and engine power.

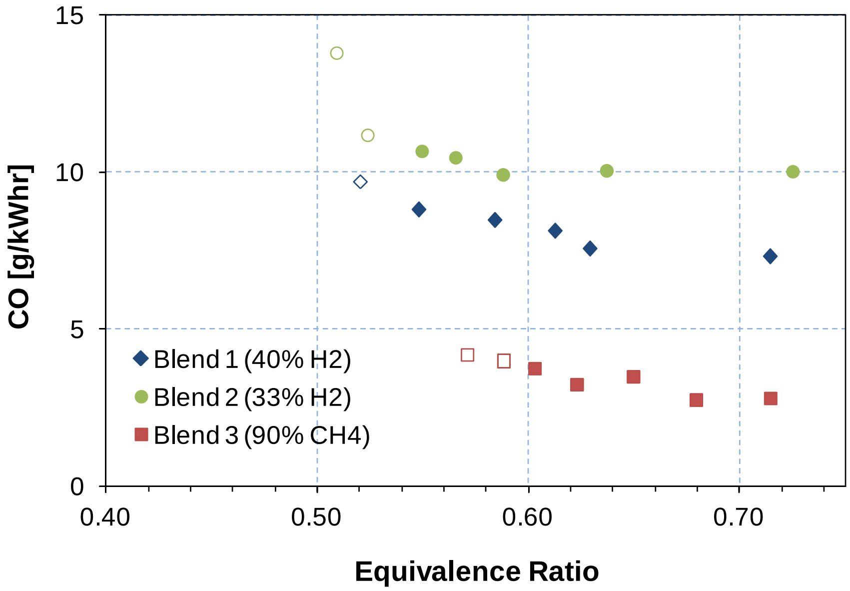
Figure 10 shows the NOx emissions recorded for all three test blends at 10 bar NMEP and a compression ratio of 9.6. For all blends, the NOx emissions drop with equivalence ratio, but the equivalence ratio is limited by the combustion stability. For a given equivalence ratio, the producer gas blends generate higher NOx emissions, but a lower equivalence ratio can be reached with these blends. This allows both producer gas blends to overall reach a lower level of NOx emissions. Figure 11 shows the brake-specific CO emissions as a function of equivalence ratio. The results show that there is no strong dependency on the equivalence ratio, but on balance, the CO emissions increase as the engine is operated under leaner equivalence ratios.

Figure 10: Brake-Specific NOx Emissions at Lean Operation



Open symbols represent data points byond the lean limit (>5% COV NMEP). The individual NOx numbers are at the projected lean limit.

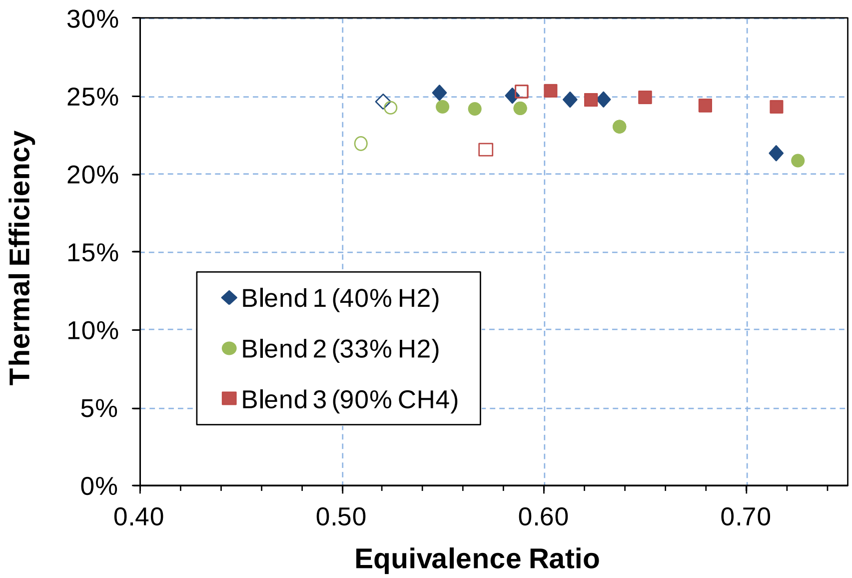
Figure 11: Brake-Specific CO Emissions at Lean Operation



Open symbols represent data points beyond the lean limit (.5%COV NMEP).

CO emissions are a strong function of the amount of CO in the fuel. Therefore, Blend 2, which has the highest CO content in the fuel, shows the highest CO emissions. Natural gas achieved much lower CO emissions, because the CO is formed only from the incomplete oxidation of hydrocarbons. Figure 12 shows the thermal efficiency as a function of the equivalence ratio. As the engine is operated at leaner conditions, the thermal efficiency increases for all blends. Only beyond the lean limit, the thermal efficiency drops due to unstable combustion. The natural gas blend has a slightly higher efficiency than the other two blends, but at very lean conditions, all three blends achieve similar efficiencies.

Figure 12: Thermal Efficiencies at Lean Operation



Open symbol represent data points beyond the lean limit (>5% COV NMEP).

1.3 Conclusions

A performance and emissions investigation of three gaseous fuel blends (two producer gas blends and a simulated natural gas blend) was carried out on a CFR engine. The Methane Number of the fuels was measured for various engine operating conditions. Ignition timing and equivalence-ratio sweeps were performed. Methane Number, pollutant emissions, brake-thermal efficiency, and combustion-pressure statistics were measured. Specific conclusions and observations are provided below.

Measured Methane Numbers and associated critical compression ratios for simulated natural gas are significantly larger than Methane Numbers and critical compression ratios for producer gas blends.

The test data for the two producer gas blends show that producer gas engines would require about 18% more boost to obtain the same power level as natural gas.

Producer gas displays faster burning rates and more stable combustion relative to simulated natural gas for the same NMEP and equivalence ratio. The combustion phasing for producer gas is shifted (advanced) by approximately 7° due to a faster burn rate.

NOx emissions of the producer gas blends are lower than for natural gas if the engine is operated at leaner conditions. If the actual producer gas contains ammonia, NOx will be larger than for the here reported producer gas blends. In all cases, an after-treatment device such as selective catalytic reduction (SCR) is necessary.

Engine operation on producer gas results in about three times as much carbon-monoxide emissions as simulated natural gas due to high levels of carbon monoxide in producer gas. This means that a large enough oxidation catalyst needs to be selected for producer gas in order to achieve the emission limits for CO.

1.3.1 Recommendations

It is recommended to verify the emission characteristics of producer gas blends that contain other contaminants such as ammonia. To reduce emissions below regulatory limits, SCR catalysts need to be tested with producer gas blends to confirm their performance and durability. These tests should include oxidation catalysts as well, because of the higher CO emissions of producer gas.

GLOSSARY

Term	Definition
aTDc	After Top Dead Center
BMEP	Brake Mean Effective Pressure
bTDc	Before Top Dead Center
CFR	Cooperative Fuel Research
COV	Coefficient of Variation
LHV	Lower Heating Value
LPP	Location of Peak Pressure
MBT	Maximum Brake Torque
MFB	Mass Fraction Burned (e.g. duration)
MN	Methane Number, measurement of knock resistance
NMEP	Net Mean Effective Pressure
PMEP	Pump Mean Effective Pressure
rcrit	Critical Compression Ratio
rpm	Revolutions Per Minute
SCR	Selective Catalytic Reduction
VOC	Volatile Organic Compounds
φ	Equivalence Ratio
EPIC	Electric Program Investment Charge
Smart Grid	Smart Grid is the thoughtful integration of intelligent technologies and innovative services that produce a more efficient, sustainable, economic, and secure electrical supply for California communities.

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